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(54) **ASPECT RATIO TRAPPING (ART) FOR FABRICATING VERTICAL SEMICONDUCTOR DEVICES**

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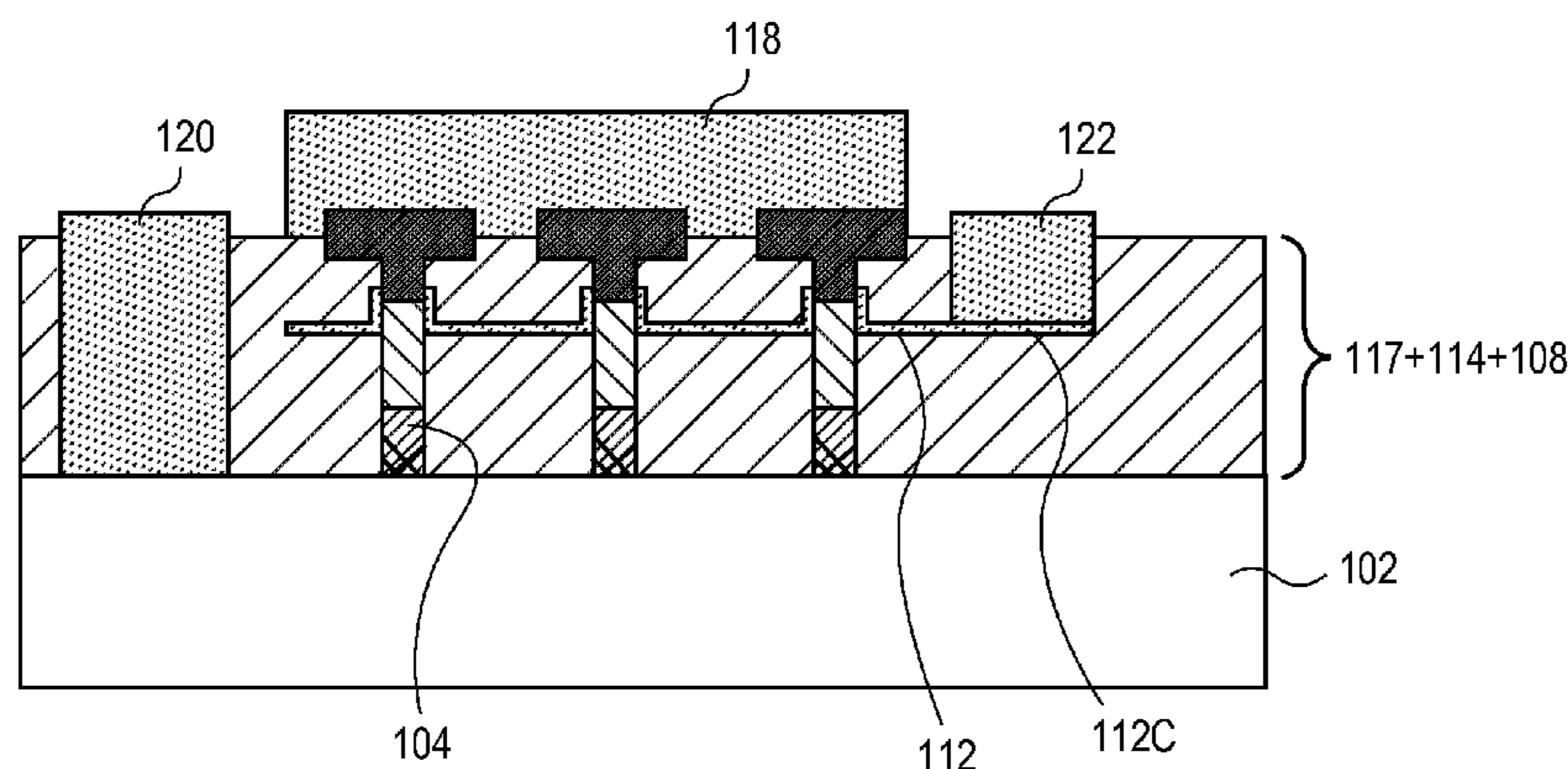
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(57) **ABSTRACT**

Aspect ratio trapping (ART) approaches for fabricating vertical semiconductor devices and vertical semiconductor devices fabricated there from are described. For example, a semiconductor device includes a substrate with an uppermost surface having a first lattice constant. A first source/drain region is disposed on the uppermost surface of the substrate and has a second, different, lattice constant. A vertical channel region is disposed on the first source/drain region. A second source/drain region is disposed on the

(Continued)



vertical channel region. A gate stack is disposed on and completely surrounds a portion of the vertical channel region.

**25 Claims, 6 Drawing Sheets**

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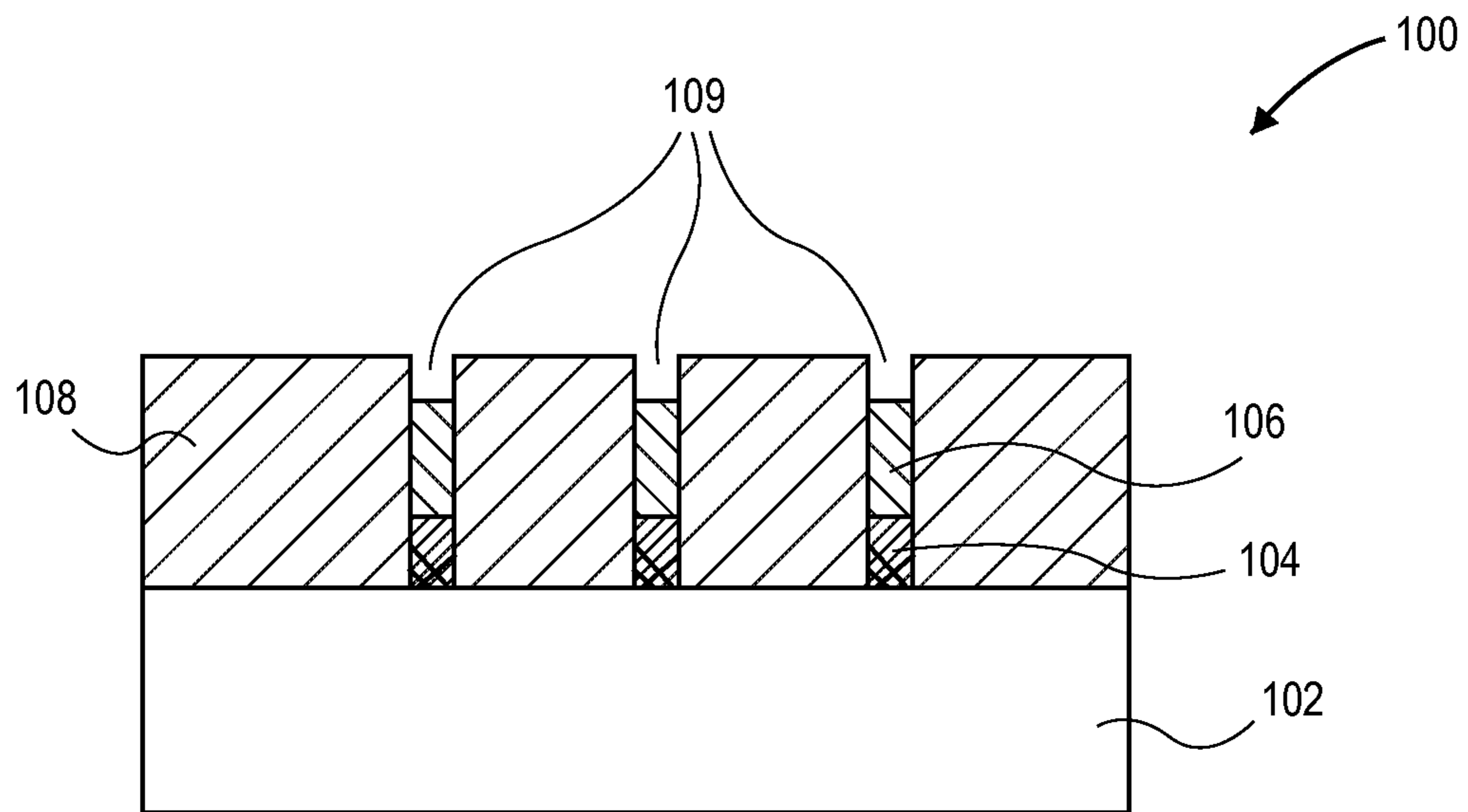


FIG. 1A

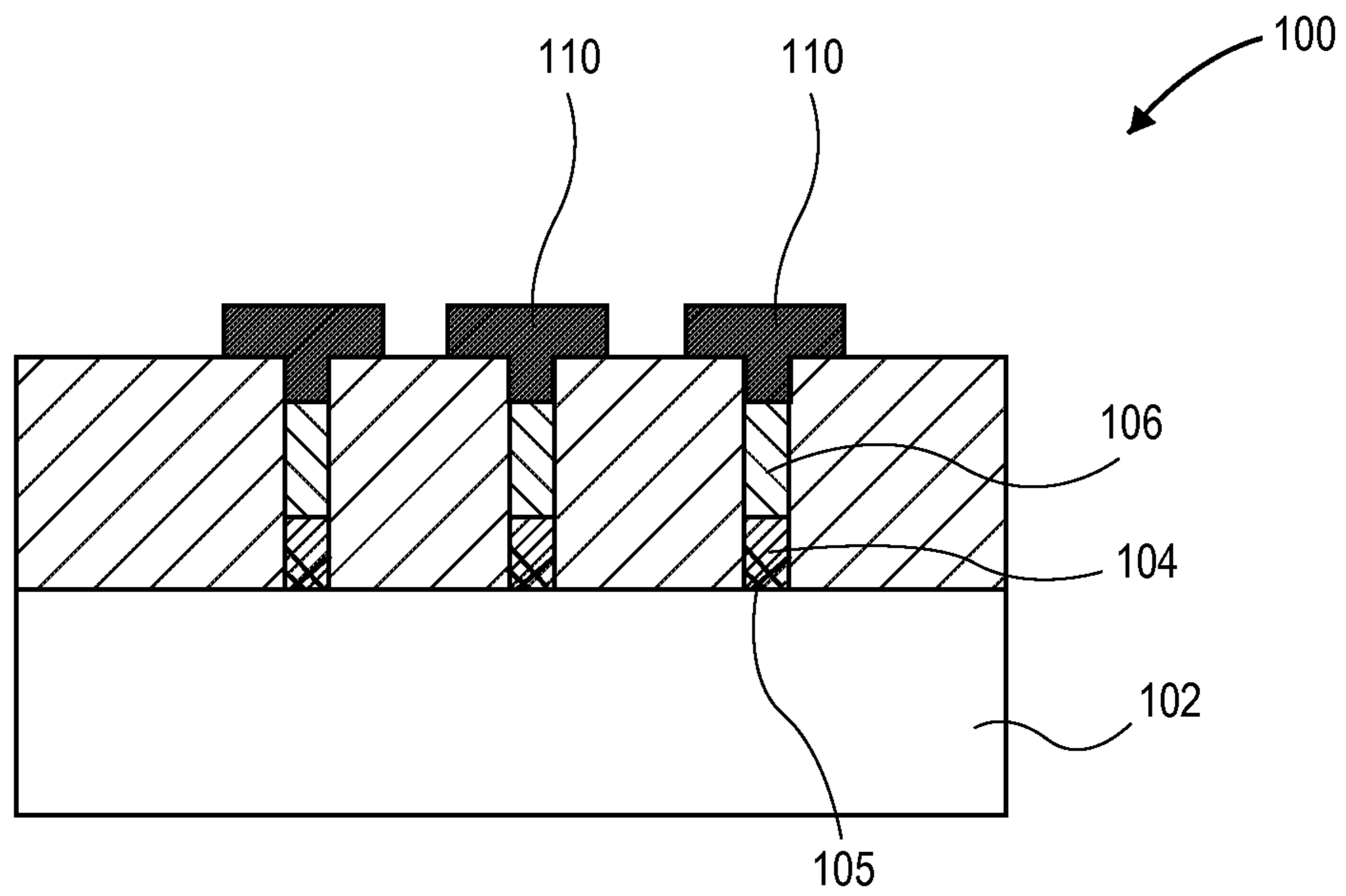
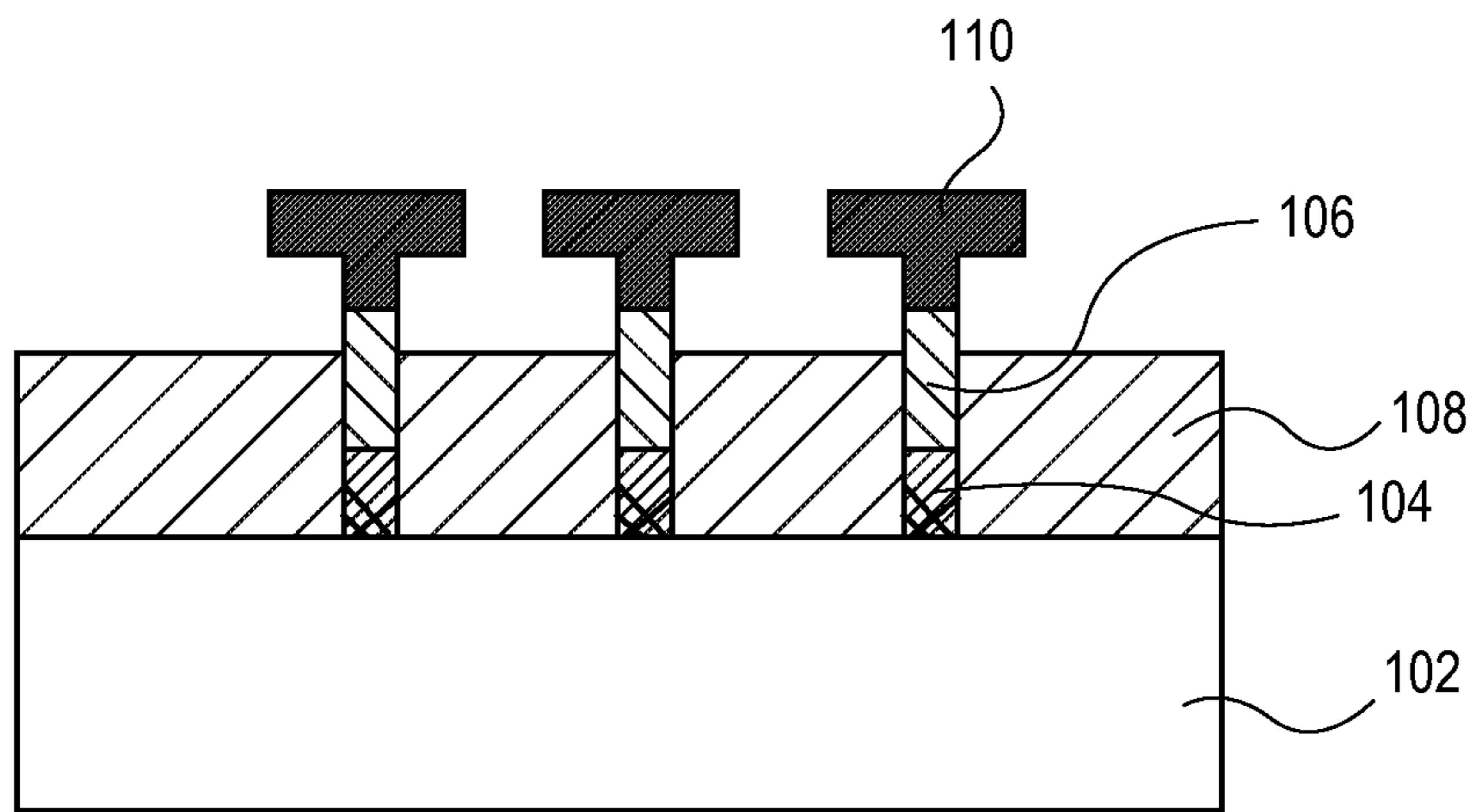
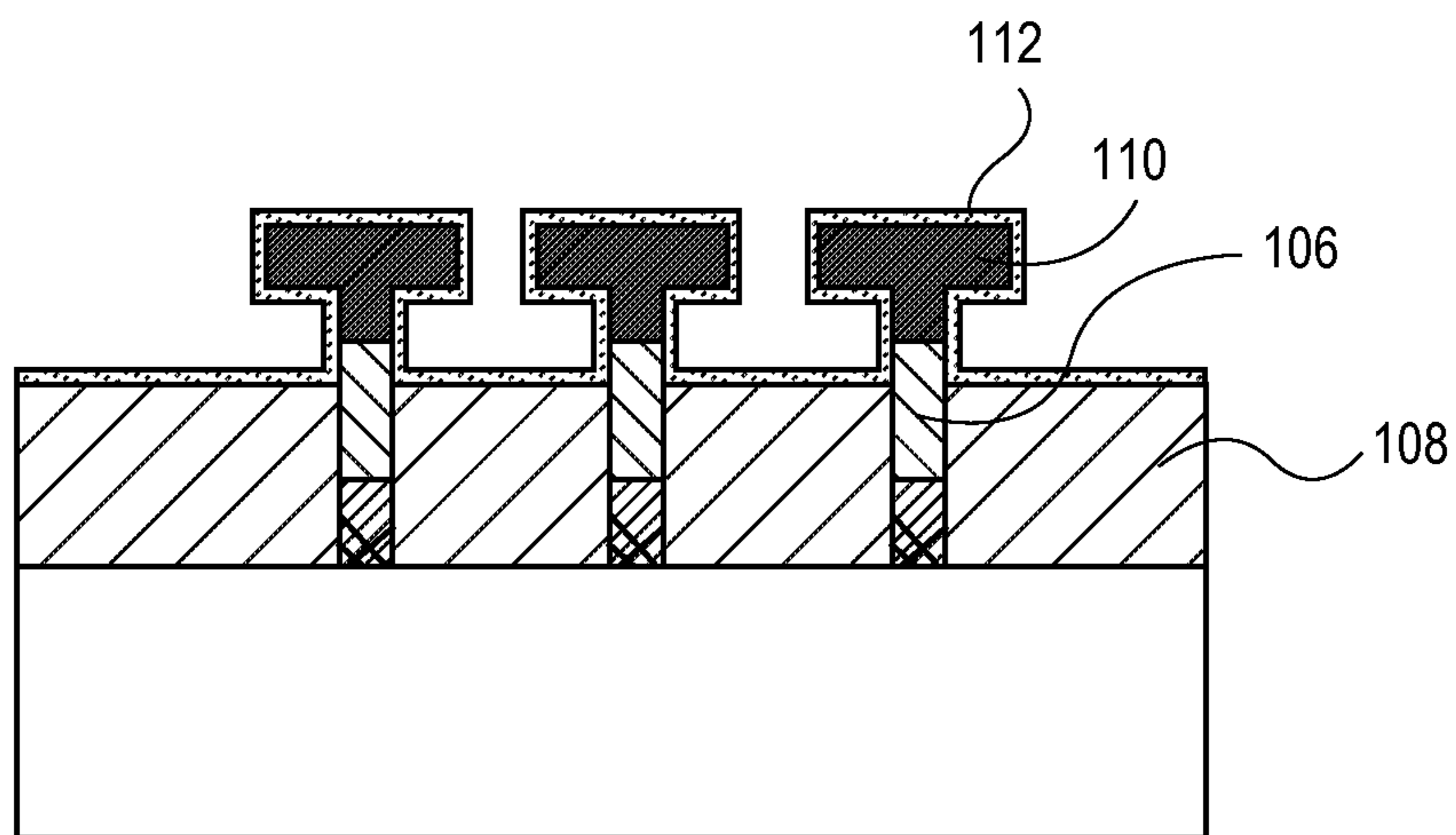


FIG. 1B



**FIG. 1C**



**FIG. 1D**

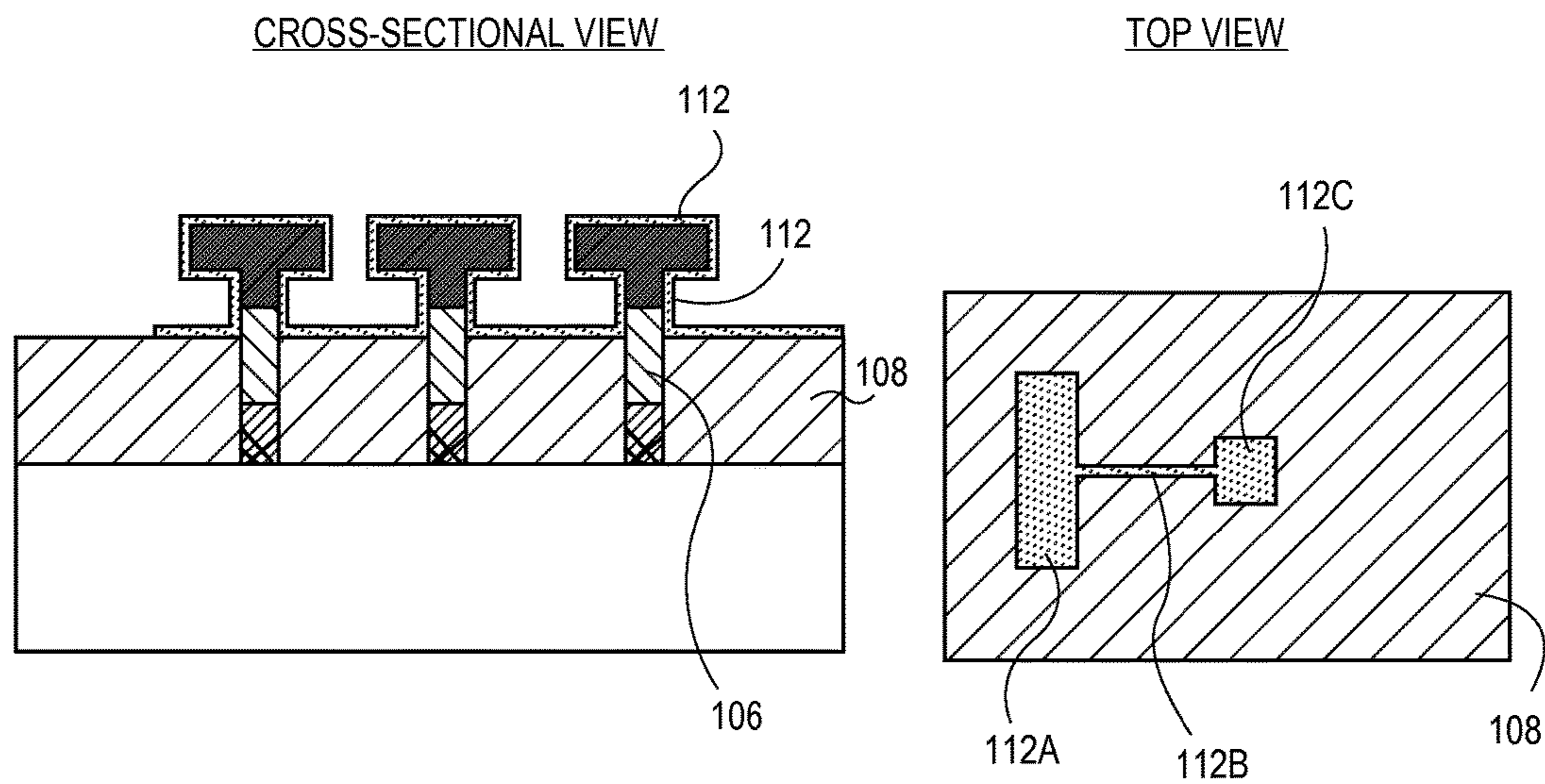


FIG. 1E

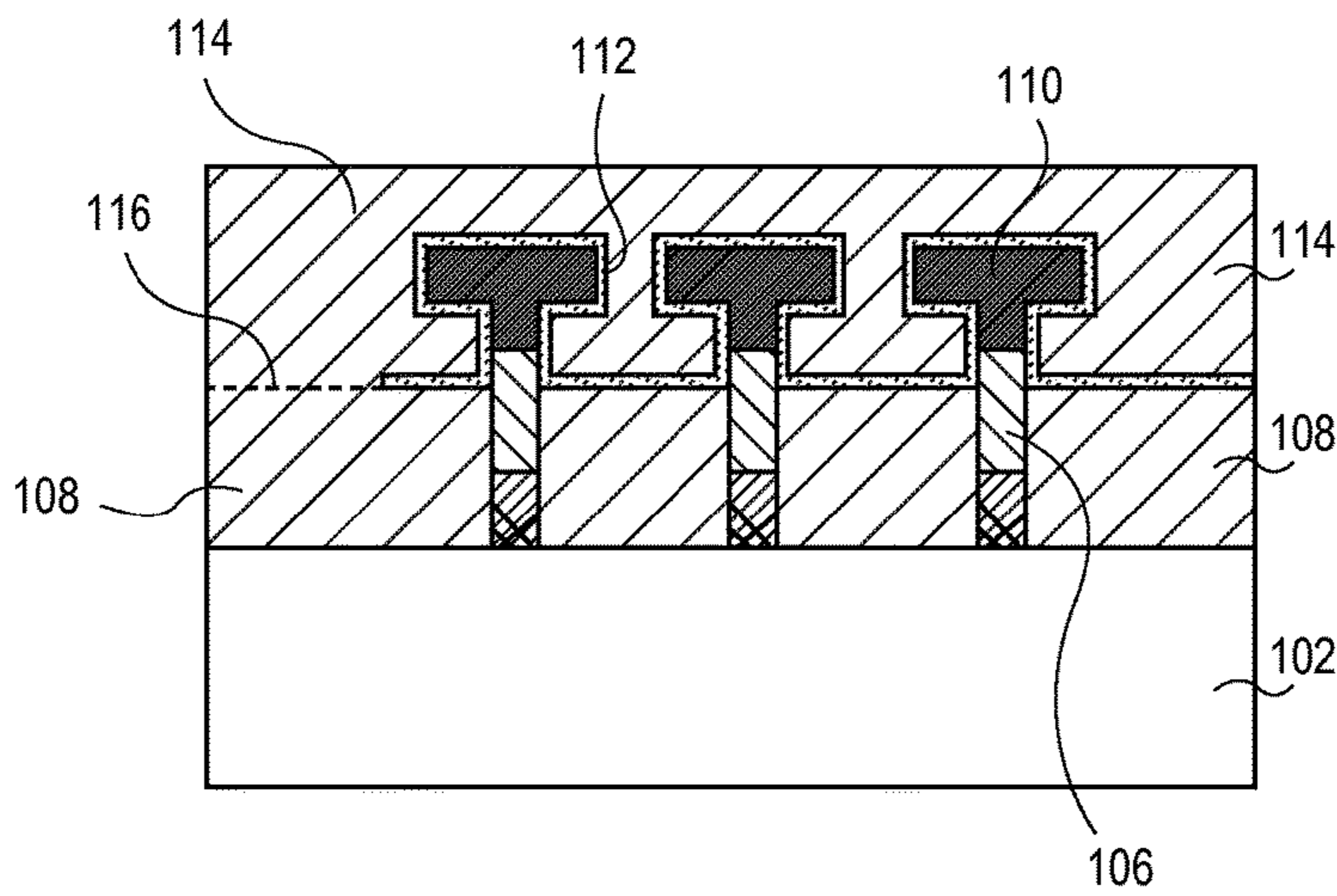
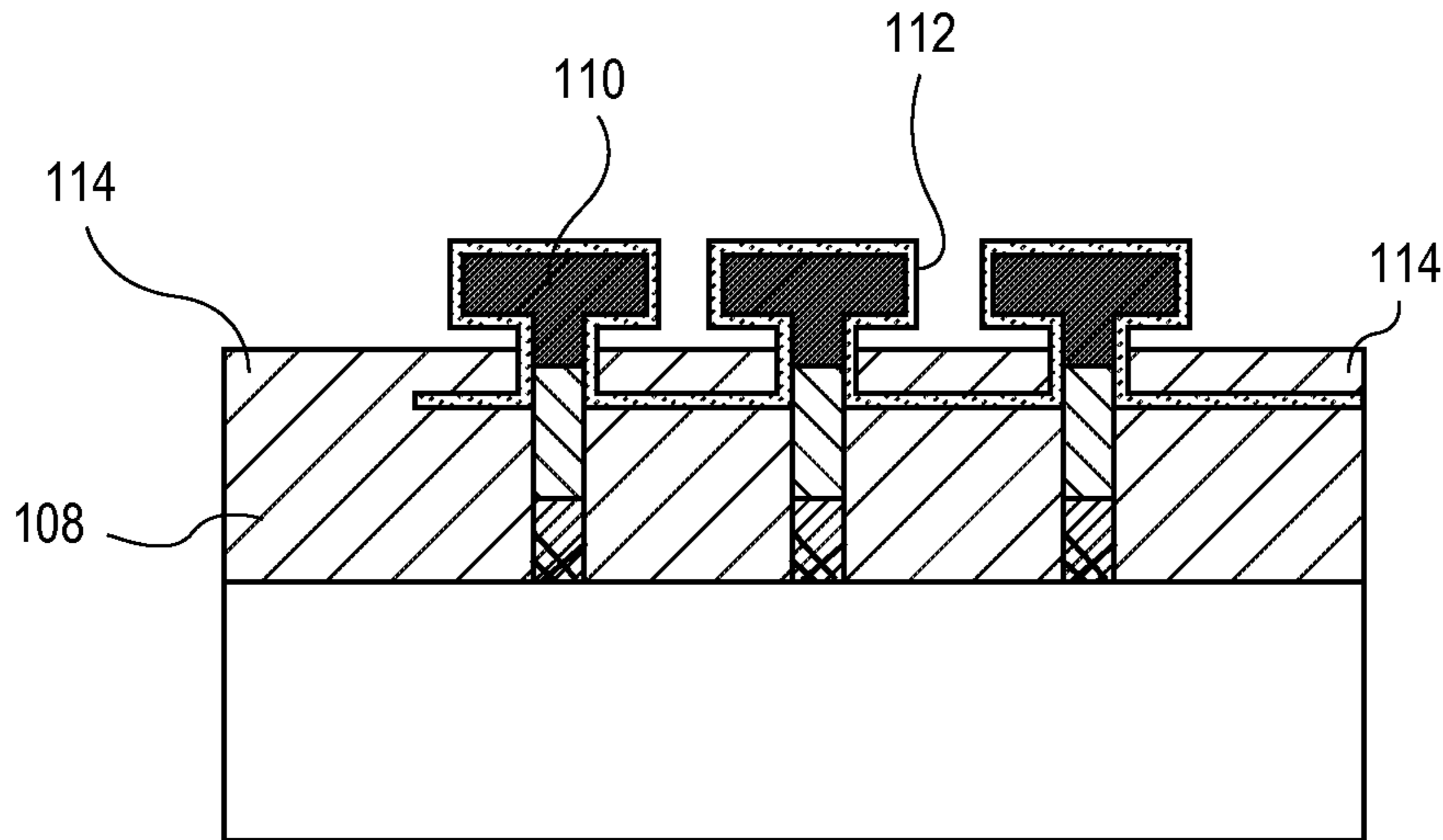
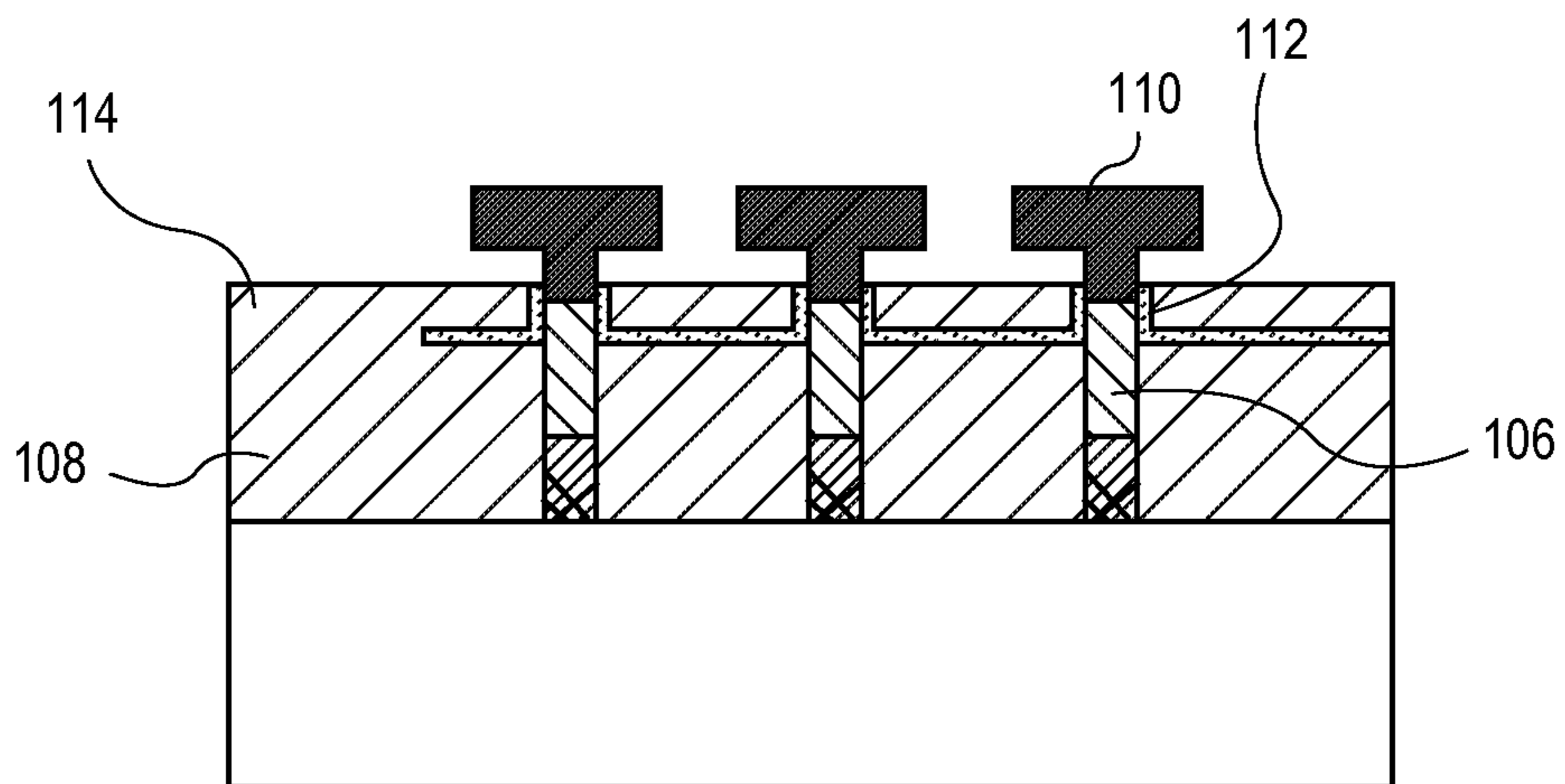


FIG. 1F



**FIG. 1G**



**FIG. 1H**

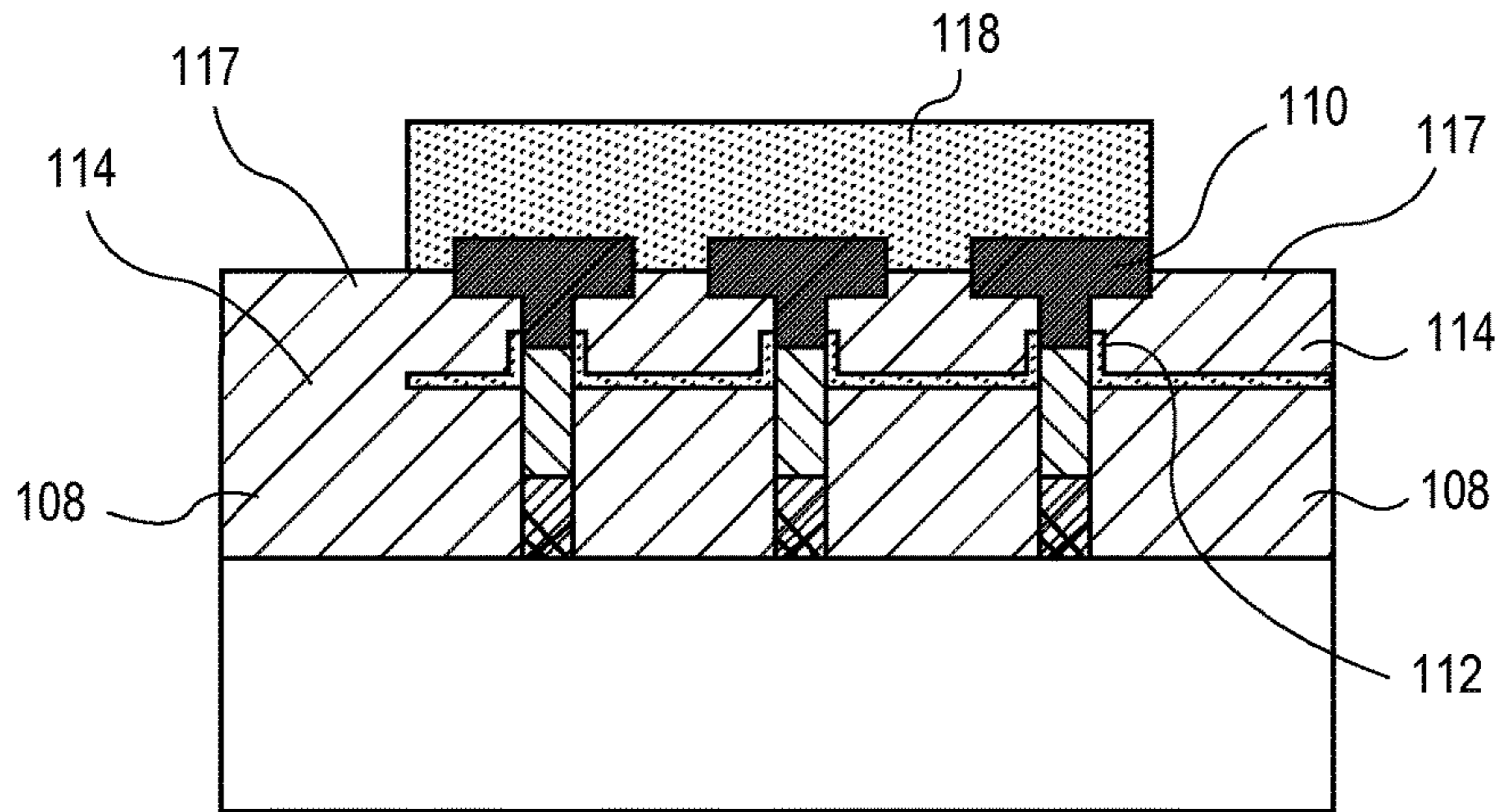


FIG. 1I

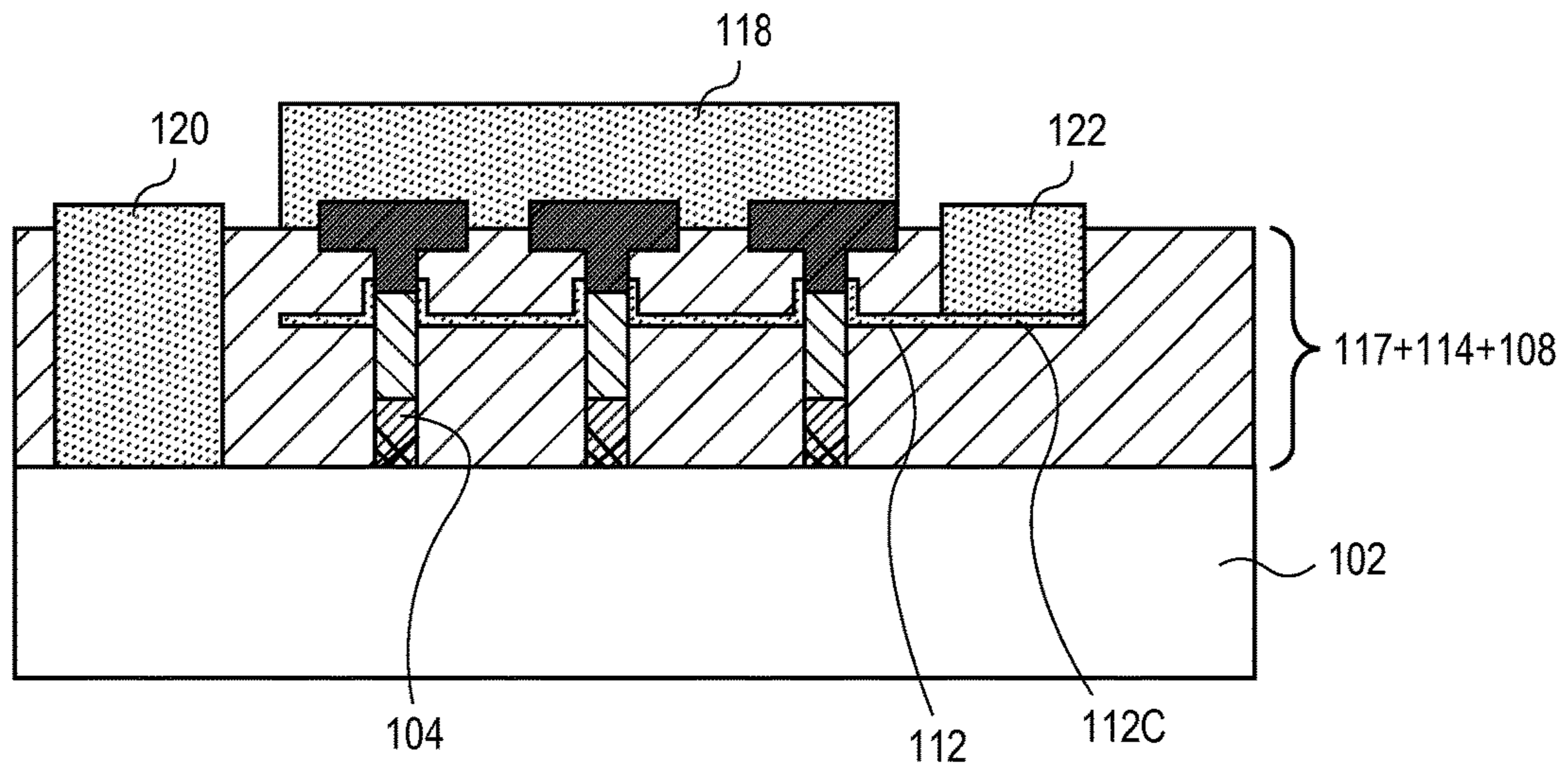


FIG. 1J

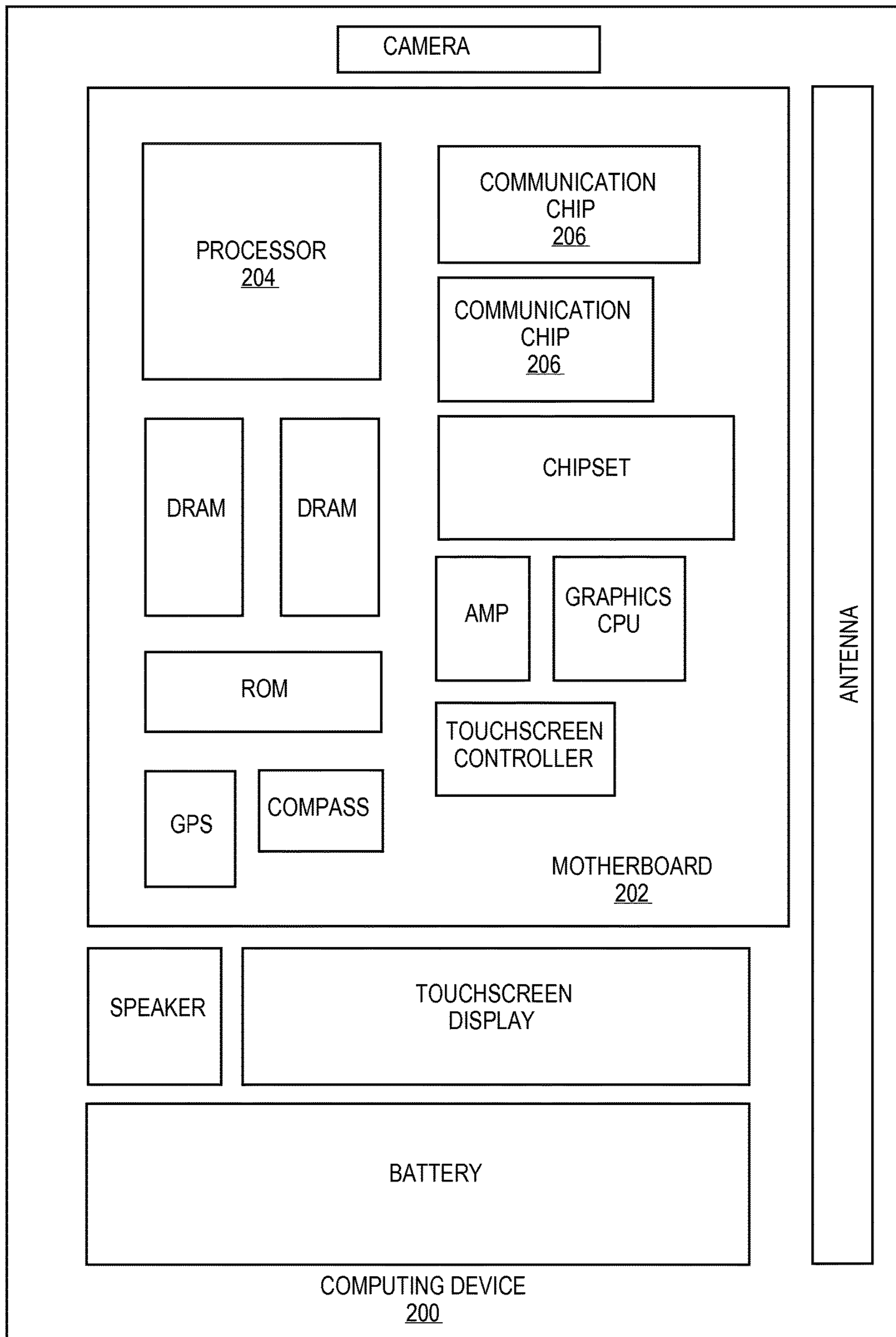


FIG. 2



## ASPECT RATIO TRAPPING (ART) FOR FABRICATING VERTICAL SEMICONDUCTOR DEVICES

### CLAIM OF PRIORITY

This application is a U.S. National Phase application under 35 U.S.C. § 371 of International Application No. PCT/US2014/032203, filed Mar. 28, 2014, entitled “ASPECT RATIO TRAPPING (ART) FOR FABRICATING VERTICAL SEMICONDUCTOR DEVICES,” the entire contents of which are incorporated herein by reference.

### TECHNICAL FIELD

Embodiments of the invention are in the field of semiconductor devices and, in particular, aspect ratio trapping (ART) approaches for fabricating vertical semiconductor devices and vertical semiconductor devices fabricated there from.

### BACKGROUND

For the past several decades, the scaling of features in integrated circuits has been a driving force behind an ever-growing semiconductor industry. Scaling to smaller and smaller features enables increased densities of functional units on the limited real estate of semiconductor chips. For example, shrinking transistor size allows for the incorporation of an increased number of memory devices on a chip, lending to the fabrication of products with increased capacity. The drive for ever-more capacity, however, is not without issue. The necessity to optimize the performance of each device becomes increasingly significant.

In the manufacture of integrated circuit devices, multi-gate transistors, such as tri-gate transistors, or gate-all-around devices, such as nanowires, have become more prevalent as device dimensions continue to scale down. Many different techniques have been attempted to reduce channel or external resistance of such transistors. However, significant improvements are still needed in the area of channel or external resistance suppression.

Additionally, many different techniques have been attempted to manufacture devices with non-Si channel materials such as SiGe, Ge, and III-V materials. However, significant process improvements are still needed to integrate these materials onto Si wafers.

Furthermore, maintaining mobility improvement and short channel control as microelectronic device dimensions scale past the 15 nanometer (nm) node provides a challenge in device fabrication. Nanowires used to fabricate devices provide improved short channel control. For example, silicon germanium ( $\text{Si}_x\text{Ge}_{1-x}$ ) nanowire channel structures (where  $x < 0.5$ ) provide mobility enhancement at respectable  $E_g$ , which is suitable for use in many conventional products which utilize higher voltage operation. Furthermore, silicon germanium ( $\text{Si}_x\text{Ge}_{1-x}$ ) nanowire channels (where  $x > 0.5$ ) provide mobility enhanced at lower  $E_g$ s (suitable for low voltage products in the mobile/handheld domain, for example). Many different techniques have been attempted to improve the mobility of transistors. However, significant improvements are still needed in the area of electron and/or hole mobility improvement for semiconductor devices.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A-1J illustrate various operations in a method of fabricating a vertical semiconductor device using aspect ratio trapping (ART), in accordance with an embodiment of the present invention, where:

FIG. 1A illustrates a cross-sectional view of a semiconductor structure following drain and vertical channel region formation through aspect ratio trapping;

FIG. 1B illustrates a cross-sectional view of the semiconductor structure of FIG. 1A following source region formation;

FIG. 1C illustrates a cross-sectional view of the semiconductor structure of FIG. 1B following isolation recess;

FIG. 1D illustrates a cross-sectional view of the semiconductor structure of FIG. 1C following gate stack formation;

FIG. 1E illustrates a cross-sectional view and corresponding plan view of the semiconductor structure of FIG. 1D following gate stack patterning;

FIG. 1F illustrates a cross-sectional view of the semiconductor structure of FIG. 1E following second isolation formation;

FIG. 1G illustrates a cross-sectional view of the semiconductor structure of FIG. 1F following second isolation recess and source region re-exposure;

FIG. 1H illustrates a cross-sectional view of the semiconductor structure of FIG. 1G following gate stack recess;

FIG. 1I illustrates a cross-sectional view of the semiconductor structure of FIG. 1H following source contact formation; and

FIG. 1J illustrates a cross-sectional view of the semiconductor structure of FIG. 1I following drain contact and gate contact formation.

FIG. 2 illustrates a computing device in accordance with one implementation of the invention.

### DESCRIPTION OF THE EMBODIMENTS

Aspect ratio trapping (ART) approaches for fabricating vertical semiconductor devices and vertical semiconductor devices fabricated there from are described. In the following description, numerous specific details are set forth, such as specific integration and material regimes, in order to provide a thorough understanding of embodiments of the present invention. It will be apparent to one skilled in the art that embodiments of the present invention may be practiced without these specific details. In other instances, well-known features, such as integrated circuit design layouts, are not described in detail in order to not unnecessarily obscure embodiments of the present invention. Furthermore, it is to be understood that the various embodiments shown in the Figures are illustrative representations and are not necessarily drawn to scale.

One or more embodiments described herein are directed to implementations of aspect ratio trapping of non-lattice-matched materials on silicon for vertical device fabrication, such as for metal oxide semiconductor field effect transistor (MOS-FET) or tunneling field effect transistor (TFET) fabrication. One or more embodiments may be applicable for high performance, low leakage logic complementary metal oxide semiconductor (CMOS) devices. In one embodiment, aspect ratio trapping is used to achieve defect reduction in the semiconductor materials used to fabricate vertical devices. Embodiments may be applicable to vertical devices, compound semiconductor (III thru V) devices, MOS\CMOS applications, etc. In one embodiment, a vertical device is defined as one having one source/drain region oriented

above another source/drain region, with a channel region running perpendicularly, between the two regions, with respect to an underlying substrate surface.

To provide context, transistors traditionally are built in the horizontal plane of silicon (Si) wafers. Embodiments described herein are directed to the fabrication of transistors of mismatched materials on Si inside aspect ratio trenches to enable defect trapping in a lowermost portion of a device layer in a vertical device architecture. Such defect trapping may enable good device performance, while the vertical device architecture may enable gate length (L<sub>g</sub>) scaling and/or leakage reduction.

More generally, embodiments described herein involve implementation of aspect ratio trapping (ART) by forming openings or trenches in an insulating layer formed on a silicon substrate (or other) surface. Non-lattice matched materials for vertical transistors are then grown directly on portions of the substrate exposed by the openings. Aspect ratio trapping may be implemented for a variety of purposes such as, but not limited to, (1) defect reduction in mismatched materials for successful integration onto Si, and (2) enabling vertical device architectures that allows for gate length (L<sub>g</sub>) scaling and leakage reduction. The unifying combination of these two advantages is a new outcome achievable by ART approaches described herein. Thus, embodiments may be used to achieve one or more of, (a) using ART openings or trenches to grow films while trapping defects, (b) growing doped source/drain (S/D) materials at opening or trench bottoms to trap defects in the S/D materials, (c) upon such defect confinement or capture, an intrinsic channel material may be grown, and (d) a top layer may then be grown to form another contact which may be grown to the top of the opening and then laterally expanded.

More specifically, embodiments described herein involve implementation of ART for the fabrication of vertical field effect transistors (FETs) for non-lattice matched materials on silicon (Si) substrates. In an exemplary embodiment, a vertical FET is fabricated by employing ART trenches to grow films while trapping defects within a targeted one of the films. For example, a doped S/D material can be grown at a trench bottom (on an exposed portion of a silicon substrate) with defects trapped therein. Upon defect capture, the channel material is grown. Following subsequent fabrication of an upper source/drain region and a gate electrode, a vertical silicon substrate/drain/channel (intrinsic)/source (D/I/S) or vertical silicon substrate/source/channel (intrinsic)/drain (S/I/D) device is formed. In one such embodiment, the source and drain regions have the same conductivity type. In another embodiment, however, a P-type tunnel field effect transistor (PTFET) is fabricated wherein the material stack is Si substrate/P/I/N. In yet another embodiment, an N-type tunnel field effect transistor (NTFET) is fabricated wherein the material stack is Si substrate/N/I/P.

In accordance with one or more embodiments described herein, advantages of approaches described herein include one or more of, but are not limited by, the use of ART to reduce defects in a channel region and to allow direct integration of III-V, and IV materials on Si; facilitation of co-integration of N/P type vertical FETs onto Si; and vertical architecture fabrication to enable L<sub>g</sub> scaling as defined by an epitaxy film thickness instead of being defined by lithography. Embodiments of the present invention can be implemented to enable CMOS integration of high performing, group III-V, IV materials onto Si in the form of vertical transistors. In an embodiment, a potential secondary effect can be derived in cases where the source or drain, or both, is not lattice-matched to the channel, providing for a strain-

inducing effect to the channel region. Such a strain-induced channel region may exhibit increased mobility.

Thus, one or more embodiments described herein enable fabrication of a vertical device through aspect ratio trapping. In an exemplary process flow, FIGS. 1A-1J illustrate various operations in a method of fabricating a vertical semiconductor device using aspect ratio trapping (ART), in accordance with an embodiment of the present invention.

FIG. 1A illustrates a cross-sectional view of a starting point semiconductor structure **100** following drain region **104** and vertical channel region **106** formation above a substrate **102** through aspect ratio trapping. In an embodiment, an isolation layer **108** is first formed over the substrate **102** and planarized. The isolation layer **108** may be referred to as a shallow trench isolation (STI) layer since it can ultimately be used to isolate neighboring devices from one another. Such an STI layer may be formed by a deposition and chemical mechanical polishing (CMP) process.

Referring again to FIG. 1A, openings **109** are then formed in isolation layer **108**, e.g., by a lithography and etch process. The openings **109** expose portions of the uppermost surface **102**. Drain region **104** is then epitaxially grown on the exposed portion of the substrate **102**. However, the growth of drain region **104** is confined by the opening(s) **109** and, thus, the aspect ratio of the drain region **104** may be trapped. Furthermore, in an embodiment, and as labeled as **105** in FIG. 1B, the drain region **104** includes lattice defects therein. In one such embodiment, the lattice defects arise since the drain region **104** is lattice mismatched from the substrate **102**. In an embodiment, the defects are effectively confined to the drain region **104** and, thus, are not propagated to additional layers formed thereon. Subsequently, the vertical channel region **106** is grown vertically from drain region **104**, e.g., by an epitaxial deposition process. In an embodiment, the vertical channel region **106** is essentially defect-free since the defects **105** were not propagated from drain region **104**. Furthermore, like the drain region **104**, the growth of the vertical channel region **106** is confined by the opening(s) **109** and, thus, the aspect ratio of the vertical channel region **106** may also be trapped.

With reference again to FIG. 1A, it is to be appreciated that three openings **109** are shown for illustrative purposes, showing three vertical channel regions **106** formed. An ultimately formed semiconductor device may include one or more vertical channel regions. It is also to be appreciated that the drain region **104** which is described herein as the lower contact region of a vertical channel region **106** can instead be a source region. That is, an ultimately fabricated device may have a lower drain region, vertical channel region and upper source region, or may have a lower source region, vertical channel region and upper drain region.

In an embodiment, substrate **102** is composed of a semiconductor material that can withstand a manufacturing process while being compatible with materials deposited or epitaxially grown thereon. In an embodiment, substrate **102** is composed of a bulk crystalline silicon, silicon/germanium or germanium layer and may be doped. In one embodiment, the concentration of silicon atoms in bulk substrate **102** is greater than 97%. In another embodiment, substrate **102** is composed of an epitaxial layer grown atop a distinct crystalline substrate, e.g. a silicon epitaxial layer grown atop a boron-doped bulk silicon mono-crystalline substrate. Substrate **102** may alternatively be composed of a group III-V material. In an embodiment, substrate **102** is composed of a III-V material such as, but not limited to, gallium nitride, gallium phosphide, gallium arsenide, indium phosphide, indium antimonide, indium gallium arsenide, aluminum

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gallium arsenide, indium gallium phosphide, or a combination thereof. In other embodiments, substrate **102** includes an intervening insulating layer, such as in the case of a silicon-on-insulator (SOI) substrate.

In an embodiment, the isolation layer **108** (also referred to herein as an insulator layer) is composed of a material suitable to ultimately electrically isolate, or contribute to the isolation of, adjacent devices. For example, in one embodiment, the isolation layer **108** is composed of a dielectric material such as, but not limited to, silicon dioxide, silicon oxy-nitride, silicon nitride, or carbon-doped silicon nitride. In an embodiment, the openings **109** formed in the isolation layer, and exposing portions of the substrate **102**, are formed by a lithography and etch process.

In an embodiment, each of the openings **109** is patterned to have a shape (from a top view perspective) that is one of a square shape, a rectangular shape, a circular shape, or an oval shape. Other geometries may be suitable as well. In one embodiment, from a top view perspective, the width and length of each of the openings **109** are approximately the same (e.g., as in the case for a square shape of circular shape), however, they need not be (as in the case for a rectangular or oval shape), again as viewed from a top view perspective.

In an embodiment, the drain region(s) **104** is formed on exposed portions of substrate **102** by a deposition process such as, but not limited to, chemical vapor deposition (CVD), atomic layer deposition (ALD), or molecular beam epitaxy (MBE). In an embodiment, the drain region **104** is in situ doped with impurity atoms. In one embodiment, the drain region **104** is doped with impurity atoms subsequent to formation. In one embodiment, the drain region **104** is in situ doped with impurity atoms and further doped subsequent to formation. It is to be appreciated that the drain region **104** may be composed of a like or different semiconductor material as that of the semiconductor material of substrate **102**. In one embodiment, the drain region **104** is composed of a crystalline silicon, silicon/germanium, germanium or germanium tin (GeSn) layer, which may be doped with a charge carrier, such as but not limited to, phosphorus, arsenic, boron or a combination thereof. In another embodiment, the drain region **104** is composed of a group III-V material such as, but not limited to, gallium nitride, gallium phosphide, gallium arsenide, indium phosphide, indium antimonide, indium gallium arsenide, aluminum gallium arsenide, indium gallium phosphide, or a combination thereof, which may be doped with a charge carrier, such as but not limited to, carbon, silicon, germanium, oxygen, sulfur, selenium or tellurium.

In an embodiment, the vertical channel region(s) **106** is formed on the drain region **102** by a deposition process such as, but not limited to, chemical vapor deposition (CVD), atomic layer deposition (ALD), or molecular beam epitaxy (MBE). It is to be appreciated that the vertical channel region **106** may be composed of a like or different semiconductor material as that of the semiconductor material of the drain region **104**. In one embodiment, the vertical channel region **106** is composed of a crystalline silicon, silicon/germanium, germanium or germanium tin (GeSn) layer. In another embodiment, the vertical channel region **206** is composed of a group III-V material such as, but not limited to, gallium nitride, gallium phosphide, gallium arsenide, indium phosphide, indium antimonide, indium gallium arsenide, aluminum gallium arsenide, indium gallium phosphide, or a combination thereof. In an embodiment, the vertical channel region is not doped (intrinsic) or is only lightly doped.

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In a particular embodiment, the vertical channel region **106** is composed essentially of silicon, is pure silicon, or is essentially pure silicon. The terms composed essentially of silicon, pure silicon or essentially pure silicon may be used to describe a silicon material composed of a very substantial amount of, if not all, silicon. However, it is to be understood that, practically, 100% pure silicon may be difficult to form in the presence of other material such as silicon germanium and, hence, could include a tiny percentage of Ge or other species. The Ge or other species may be included as an unavoidable impurity or component during deposition of Si or may "contaminate" the Si upon diffusion during post deposition processing. As such, embodiments described herein directed to a Si channel portion may include Si channel portions that contain a relatively small amount, e.g., "impurity" level, non-Si atoms or species, such as Ge. By contrast, regions such as a regrown source region may include a significant amount of germanium, e.g., in the form of a silicon germanium layer.

FIG. 1B illustrates a cross-sectional view of the structure of FIG. 1A following source region formation. In accordance with an embodiment of the present invention, a source region **110** is formed on the uppermost, exposed surface of the vertical channel region **106**. In one embodiment, as depicted, the uppermost surface of the vertical channel region **106** is below the height of the STI layer **108**. As such, at least a lower portion of the source region is confined by the opening(s) **109** and, thus, the aspect ratio of the source region **110** may be trapped. In one embodiment, a second portion of the source region is formed above and expands over a portion of the STI layer **108**, as is also depicted in FIG. 1B. Nonetheless, it is to be appreciated that, in one embodiment, epitaxial formation of the source region **110** is selective in that the growth only occurs on/from the vertical channel region **106** and does not initiate on the STI layer **108**.

In an embodiment, the source region(s) **110** is formed on vertical channel region **106** by a deposition process such as, but not limited to, chemical vapor deposition (CVD), atomic layer deposition (ALD), or molecular beam epitaxy (MBE). In one embodiment, the source region **110** is in situ doped with impurity atoms. In one embodiment, the source region **110** is doped with impurity atoms subsequent to formation. In one embodiment, the source region **110** is in situ doped with impurity atoms and further doped subsequent to formation. It is to be appreciated that the source region **110** may be composed of a like or different semiconductor material as that of the vertical channel region **110**. In one embodiment, the source region **110** is composed of a crystalline silicon, silicon/germanium, germanium, or germanium tin layer, which may be doped with a charge carrier, such as but not limited to, phosphorus, arsenic, boron or a combination thereof. In another embodiment, the source region **110** is composed of a group III-V material such as, but not limited to, gallium nitride, gallium phosphide, gallium arsenide, indium phosphide, indium antimonide, indium gallium arsenide, aluminum gallium arsenide, indium gallium phosphide, or a combination thereof, which may be doped with a charge carrier, such as but not limited to, carbon, silicon, germanium, oxygen, sulfur, selenium or tellurium.

As mentioned briefly above, the source region **110**, the drain region **104**, or both may be fabricated to impart strain to the vertical channel region **106**. In an embodiment, the vertical channel region **106** is a uniaxially strained vertical channel region with the strain along the channel in a direction vertical to the substrate **102** surface, i.e., running between source and drain regions. Such a uniaxially strained

vertical channel region **106** may be uniaxially strained with tensile strain or with compressive strain, e.g., for NMOS or PMOS, respectively. In one embodiment, the lattice constant of the source region **110**, the drain region **104**, or both, is smaller than the lattice constant of the vertical channel region **106**, and the source region **110**, the drain region **104**, or both, imparts a compressive uniaxial strain to the vertical channel region **106**. In another embodiment, the lattice constant of the source region **110**, the drain region **104**, or both, is larger than the lattice constant of the vertical channel region **106**, and the source region **110**, the drain region **104**, or both, imparts a tensile uniaxial strain to the vertical channel region **106**. In one embodiment, the vertical channel region **106** is composed of  $\text{Si}_x\text{Ge}_{1-x}$ , and the source region **110**, the drain region **104**, or both, is composed of  $\text{Si}_y\text{Ge}_{1-y}$ , where  $0 \leq x, y \leq 1$  and  $x \neq y$ . In another embodiment, the vertical channel region **106** is composed of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ,  $\text{In}_x\text{Ga}_{1-x}\text{As}$ ,  $\text{In}_x\text{Ga}_{1-x}\text{P}$  or  $\text{Al}_x\text{In}_{1-x}\text{Sb}$ , and the source region **110**, the drain region **104**, or both, is composed of  $\text{Al}_y\text{Ga}_{1-y}\text{As}$ ,  $\text{In}_y\text{Ga}_{1-y}\text{As}$ ,  $\text{In}_y\text{Ga}_{1-y}\text{P}$  or  $\text{Al}_y\text{In}_{1-y}\text{Sb}$ , respectively, where  $0 \leq x, y \leq 1$  and  $x \neq y$ .

FIG. **1C** illustrates a cross-sectional view of the structure of FIG. **1B** following isolation recess. In an embodiment, a portion, but not all, of the STI layer **108** is recessed to expose a portion of the vertical channel region **106**. The recessing represents initiation of the gate electrode formation process which is elaborated on below, in accordance with FIGS. **1D** and **1E**. In one embodiment, a wet etch based on aqueous hydrofluoric acid is used to recess the STI layer **108**. However, dry etch processing may be used instead of, or in conjunction with, such a wet etch process. It is to be appreciated that, in accordance with one embodiment, FIG. **1C** depicts an extent of recess suitable for a vertical TFET. In another embodiment, for a MOSFET, the recess is performed to an extent that the gate stack can surround essentially the entire channel and equidistant to both the S/D, whereas the TFET would have the gate stack over the source/channel region, away from the drain side.

FIG. **1D** illustrates a cross-sectional view of the structure of FIG. **1C** following gate stack formation. In an embodiment, a gate dielectric layer and gate electrode layer (shown combined as stack **112**) is formed on the entire structure of FIG. **1C**. Most importantly, the gate stack **112** is formed on all surfaces of the vertical channel region **106** exposed during STI layer **108** recess. Consequentially, in one embodiment, the gate stack **112** is also formed on all exposed surfaces of the source region **110**, as is depicted in FIG. **1D**. In one embodiment, the layers of the gate stack **112** are formed by atomic layer deposition (ALD) and/or chemical vapor deposition (CVD) and are thus conformal with the structure of FIG. **1C**, as is also depicted in FIG. **1D**.

In accordance with an embodiment of the present invention, gate stack **112** includes a metal gate electrode and a high-K gate dielectric layer. For example, in one embodiment, the gate dielectric layer is composed of a material such as, but not limited to, hafnium oxide, hafnium oxy-nitride, hafnium silicate, lanthanum oxide, zirconium oxide, zirconium silicate, tantalum oxide, barium strontium titanate, barium titanate, strontium titanate, yttrium oxide, aluminum oxide, lead scandium tantalum oxide, lead zinc niobate, or a combination thereof. Furthermore, a portion of gate dielectric layer may include a layer of native oxide formed from the outermost few layers of the vertical channel region **106**. In an embodiment, the gate dielectric layer is composed of an outermost high-k portion and an inner portion composed of an oxide of a semiconductor material. In one embodiment, the gate dielectric layer is composed of an outermost

portion of hafnium oxide and an inner portion of silicon dioxide or silicon oxy-nitride.

In one embodiment, the gate electrode is composed of a metal layer such as, but not limited to, metal nitrides, metal carbides, metal silicides, metal aluminides, hafnium, zirconium, titanium, tantalum, aluminum, ruthenium, palladium, platinum, cobalt, nickel or conductive metal oxides. In a specific embodiment, the gate electrode is composed of a non-workfunction-setting fill material formed to surround a metal workfunction-setting layer disposed around the gate dielectric layer.

FIG. **1E** illustrates a cross-sectional view and corresponding plan view of the structure of FIG. **1D** following gate stack **112** patterning. In an embodiment, since the gate stack **112** was formed conformally and without selectivity to different surfaces, the gate stack **112** is patterned, e.g., by a lithography and etch process. In one such embodiment, the gate stack **112** is patterned to leave a portion of the gate stack on the exposed portions of the vertical channel region **106** and the source region **110**, and to leave a portion along the surface of the STI layer **108** for ultimate gate contact formation. For example, as seen from the top view, portion **112A** of the patterned gate stack **112** is the portion on the source region **110**, portion **112C** provides a location for later gate contact/via landing, and portion **112B** is a line coupling the portions **112A** and **112B**. In one embodiment, the gate stack **112** is patterned by a dry etch process, wet etch process, or combination thereof, suitable to pattern the layers of the gate stack **112** without significantly impacting the STI layer **108**. In an embodiment, subsequent to patterning the gate stack **112**, a portion of the gate stack **112** completely surrounds at least a portion of each of the vertical channel regions **106**. As mentioned briefly above, an ultimately fabricated device may be based on one or more vertical channel regions, with the specific example depicted based on three vertical channel regions.

FIG. **1F** illustrates a cross-sectional view of the structure of FIG. **1E** following second isolation formation. In an embodiment, a second isolation layer **114** is formed to cover the source regions **110**. In one such embodiment, the second isolation layer is composed of the same material as the STI layer **108**, and the layers are essentially indiscernible from one another. However, in other embodiments, a seam **116** is observable between layers **108** and **114**, as is depicted, as depicted in FIG. **1F**. The second isolation layer may be formed by a deposition process, such as a CVD process, and may be planarized, e.g., by a CMP process. In any case, the second isolation layer can effectively be implemented as a shallow trench isolation structure for isolating devices from one another.

FIG. **1G** illustrates a cross-sectional view of the structure of FIG. **1F** following second isolation layer **114** recess and source region **110** re-exposure. In an embodiment, a portion, but not all, of the second isolation layer **114** is recessed to expose at least a portion of the source region **110**. In one embodiment, the second isolation layer **114** is recessed to a level below the widest portion of the source region **110**, as is depicted in FIG. **1G**. In one embodiment, a wet etch is used to recess the second isolation layer **114**. However, dry etch processing may be used instead of, or in conjunction with, such a wet etch process.

FIG. **1H** illustrates a cross-sectional view of the semiconductor structure of FIG. **1G** following gate stack recess. In an embodiment, exposed portions of the gate stack **112** are removed from the source region **110**. By removing these portions of the gate stack **112**, the surface of the source region **110** that protrudes above the second isolation layer

114 is not covered by gate stack 112 material, as is depicted in FIG. 1H. In one embodiment, a wet etch is used to remove the exposed portions of the gate stack 112. However, dry etch processing may be used instead of, or in conjunction with, such a wet etch process. Following recess of gate stack, a third isolation layer 117 may be added (e.g., by deposition an etch back) to expose only upper portions of source regions 110, as depicted in FIG. 1I, described below.

FIG. 1I illustrates a cross-sectional view of the structure of FIG. 1H following source contact formation. In an embodiment, a source contact 118 is formed to cover substantially all of the portions of source region 110 protruding above the third isolation layer 117. In one embodiment, the source contact 118 is formed by a subtractive deposition and etch process. In another embodiment, the material of source contact 118 is formed by selective growth on the portion of source regions 110 protruding above the third isolation layer 117. It is to be appreciated that the specific depiction of a common source contact for three source regions is for one particular embodiment. Other groupings of one or more source regions with a common source contact are also considered within the spirit and scope of embodiments of the present invention.

In an embodiment, source contact 118 is composed of a conductive material. In one such embodiment, source contact 118 is composed of a metal or metallic material. The metal or metallic material may be a pure metal, such as tungsten, nickel, or cobalt, or may be an alloy such as a metal-metal alloy or a metal-semiconductor alloy (e.g., such as a silicide material).

FIG. 1J illustrates a cross-sectional view of the semiconductor structure of FIG. 1I following drain contact and gate contact formation. In an embodiment, the STI structure (including the third isolation layer 117, the second isolation layer 114, and the STI layer 108) is patterned with via/contact holes to expose portions of the substrate 102 coupled to the drain region(s) 104 and to expose a portion of the gate stack 112 (e.g., the portion 112C described in association with FIG. 1E). A drain contact 120 and a gate contact 122 may then be fabricated by a metal deposition and planarization process or by a selective growth process. In either case, in one embodiment, the material of the drain contact 120 and the gate contact 122 is substantially the same as the material of the source contact 118. Although, in other embodiments, the material of the drain contact 120 and the gate contact 122 is different from the material of the source contact 118. In an embodiment, the via/contact holes formed to expose portions of the substrate 102 coupled to the drain region 104 and to expose a portion of the gate stack 112 are fabricated using a lithography and etch process. It is to be appreciated that, as depicted, the drain contact may not be formed directly on the confined drain region, but rather on a portion of substrate 102 that is electrically coupled with drain region(s) 104.

Referring again to FIG. 1J, a semiconductor device based on a vertical channel region may be a semiconductor device incorporating a gate surrounding the channel region, and a pair of vertically oriented source/drain regions. In an embodiment, the semiconductor device is a MOS-FET. In one embodiment, the semiconductor device is a vertical MOS-FET and is an isolated device or is one device in a plurality of nested devices. It is to be appreciated that the structures resulting from the above exemplary processing scheme, e.g., the structure from FIG. 1J, may be used in a same or similar form for subsequent processing operations to complete device fabrication, such as PMOS and/or NMOS device fabrication. In such cases, opposing source and drain regions have a same conductivity type. As will be

appreciated for a typical integrated circuit, both N- and P-channel transistors may be fabricated on a single substrate to form a CMOS integrated circuit. In other embodiments, a tunnel field effect transistor (TFET) is fabricated having opposing source and drain regions of opposite conductivity type. In either case, additional interconnect wiring may be fabricated in order to integrate such devices into an integrated circuit. Furthermore, it is to be appreciated that a single device may include only one, or more than one (e.g., by use of a common gate stack), of a plurality of vertical channel regions fabricated above a substrate. FIG. 1I illustrates a particular embodiment where three vertical channel regions share a common gate electrode and common source/drain regions.

It is to be appreciated that not all aspects of the processes described above need be practiced to fall within the spirit and scope of embodiments of the present invention. Also, the processes described herein may be used to fabricate one or a plurality of semiconductor devices. The semiconductor devices may be transistors or like devices. For example, in an embodiment, the semiconductor devices are metal-oxide semiconductor (MOS) transistors for logic or memory, or are bipolar transistors. Also, in an embodiment, the semiconductor devices have a three-dimensional architecture, such as a gate-all-around device. One or more embodiments may be particularly useful for fabricating semiconductor devices at a 10 nanometer (10 nm) or smaller technology node. Embodiments herein may be applicable for improving transistor layout density and for mitigating trends toward increases in contact resistance.

FIG. 2 illustrates a computing device 200 in accordance with one implementation of the invention. The computing device 200 houses a board 202. The board 202 may include a number of components, including but not limited to a processor 204 and at least one communication chip 206. The processor 204 is physically and electrically coupled to the board 202. In some implementations the at least one communication chip 206 is also physically and electrically coupled to the board 202. In further implementations, the communication chip 206 is part of the processor 204.

Depending on its applications, computing device 200 may include other components that may or may not be physically and electrically coupled to the board 202. These other components include, but are not limited to, volatile memory (e.g., DRAM), non-volatile memory (e.g., ROM), flash memory, a graphics processor, a digital signal processor, a crypto processor, a chipset, an antenna, a display, a touchscreen display, a touchscreen controller, a battery, an audio codec, a video codec, a power amplifier, a global positioning system (GPS) device, a compass, an accelerometer, a gyroscope, a speaker, a camera, and a mass storage device (such as hard disk drive, compact disk (CD), digital versatile disk (DVD), and so forth).

The communication chip 206 enables wireless communications for the transfer of data to and from the computing device 200. The term “wireless” and its derivatives may be used to describe circuits, devices, systems, methods, techniques, communications channels, etc., that may communicate data through the use of modulated electromagnetic radiation through a non-solid medium. The term does not imply that the associated devices do not contain any wires, although in some embodiments they might not. The communication chip 206 may implement any of a number of wireless standards or protocols, including but not limited to Wi-Fi (IEEE 802.11 family), WiMAX (IEEE 802.16 family), IEEE 802.20, long term evolution (LTE), Ev-DO, HSPA+, HSDPA+, HSUPA+, EDGE, GSM, GPRS, CDMA,

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TDMA, DECT, Bluetooth, derivatives thereof, as well as any other wireless protocols that are designated as 3G, 4G, 5G, and beyond. The computing device **200** may include a plurality of communication chips **206**. For instance, a first communication chip **206** may be dedicated to shorter range wireless communications such as Wi-Fi and Bluetooth and a second communication chip **206** may be dedicated to longer range wireless communications such as GPS, EDGE, GPRS, CDMA, WiMAX, LTE, Ev-DO, and others.

The processor **204** of the computing device **200** includes an integrated circuit die packaged within the processor **204**. In some implementations of the invention, the integrated circuit die of the processor includes one or more devices, such as MOS-FET transistors built in accordance with implementations of the invention. The term "processor" may refer to any device or portion of a device that processes electronic data from registers and/or memory to transform that electronic data into other electronic data that may be stored in registers and/or memory.

The communication chip **206** also includes an integrated circuit die packaged within the communication chip **206**. In accordance with another implementation of the invention, the integrated circuit die of the communication chip includes one or more devices, such as MOS-FET transistors built in accordance with implementations of the invention.

In further implementations, another component housed within the computing device **200** may contain an integrated circuit die that includes one or more devices, such as MOS-FET transistors built in accordance with implementations of the invention.

In various implementations, the computing device **200** may be a laptop, a netbook, a notebook, an ultrabook, a smartphone, a tablet, a personal digital assistant (PDA), an ultra mobile PC, a mobile phone, a desktop computer, a server, a printer, a scanner, a monitor, a set-top box, an entertainment control unit, a digital camera, a portable music player, or a digital video recorder. In further implementations, the computing device **200** may be any other electronic device that processes data.

Thus, embodiments of the present invention include aspect ratio trapping (ART) approaches for fabricating vertical semiconductor devices and vertical semiconductor devices fabricated there from.

In an embodiment, a semiconductor device includes a substrate with an uppermost surface having a first lattice constant. A first source/drain region is disposed on the uppermost surface of the substrate and has a second, different, lattice constant. A vertical channel region is disposed on the first source/drain region. A second source/drain region is disposed on the vertical channel region. A gate stack is disposed on and completely surrounds a portion of the vertical channel region.

In one embodiment, the semiconductor device further includes a plurality of lattice defects confined to the first source/drain region. The vertical channel region is essentially defect-free.

In one embodiment, the first and second source/drain regions are composed of a semiconductor material different from a semiconductor material of the vertical channel region.

In one embodiment, the semiconductor material of the first and second source/drain regions is lattice mismatched from the semiconductor material of the vertical channel region, and the first and second source/drain regions impart a strain to the vertical channel region.

In one embodiment, the semiconductor device further includes a first contact disposed on the uppermost surface of

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the substrate and electrically coupled to the first source/drain region through the substrate. A second contact is disposed on the second source/drain region. A gate contact is disposed on a horizontal extension of the gate stack.

In one embodiment, the first source/drain region is a drain region, and the second source/drain region is a source region.

In one embodiment, the first source/drain region is a source region, and the second source/drain region is a drain region.

In one embodiment, the gate stack includes a high-k gate dielectric layer and a metal gate electrode.

In one embodiment, a conductivity type of the first source/drain region is the same as a conductivity type of the second source/drain region, and the semiconductor device is a MOS-FET device.

In one embodiment, a conductivity type of the first source/drain region is opposite to a conductivity type of the second source/drain region, and the semiconductor device is a tunnel FET device.

In an embodiment, a semiconductor device, includes a substrate having a surface. A first source/drain region is disposed on the surface of the substrate. A vertical channel region is disposed on the first source/drain region. A plurality of lattice defects is confined to the first source/drain region. The vertical channel region is essentially defect-free. A second source/drain region is disposed on the vertical channel region. A gate stack is disposed on and completely surrounds a portion of the vertical channel region.

In one embodiment, the first and second source/drain regions are composed of a semiconductor material different from a semiconductor material of the vertical channel region.

In one embodiment, the semiconductor material of the first and second source/drain regions is lattice mismatched from the semiconductor material of the vertical channel region, and the first and second source/drain regions impart a strain to the vertical channel region.

In one embodiment, the semiconductor device further includes a first contact disposed on the surface of the substrate and electrically coupled to the first source/drain region through the substrate. A second contact is disposed on the second source/drain region. A gate contact is disposed on a horizontal extension of the gate stack.

In one embodiment, the first source/drain region is a drain region, and the second source/drain region is a source region.

In one embodiment, the first source/drain region is a source region, and the second source/drain region is a drain region.

In one embodiment, the gate stack includes a high-k gate dielectric layer and a metal gate electrode.

In one embodiment, a conductivity type of the first source/drain region is the same as a conductivity type of the second source/drain region, and the semiconductor device is a MOS-FET device.

In one embodiment, a conductivity type of the first source/drain region is opposite to a conductivity type of the second source/drain region, and the semiconductor device is a tunnel FET device.

In an embodiment, a method of fabricating a semiconductor device involves forming an insulator layer on a surface of a substrate. The method also involves patterning the insulator layer to form an opening in the insulator layer, the opening exposing a portion of the surface of the substrate. The method also involves forming a first source/drain region in the opening, on the surface of the substrate. The

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method also involves forming a vertical channel region in the opening, on the first source/drain region. The method also involves forming a second source/drain region in the opening, on the vertical channel region. The method also involves recessing the insulator layer to expose a portion of the vertical channel region. The method also involves forming a gate stack on and completely surrounding an exposed portion of the vertical channel region.

In one embodiment, forming the first source/drain region involves forming a plurality of lattice defects confined to the first source/drain region, wherein the vertical channel region is formed essentially defect-free.

In one embodiment, forming the first source/drain region involves forming the first source/drain region having a lattice constant different than a lattice constant of the surface of the substrate.

In one embodiment, forming the second source/drain region in the opening involves forming a first portion of the second source/drain region in the opening, and forming a second portion of the second source/drain region above the opening and on a portion of an uppermost surface of the insulator layer.

In one embodiment, forming the first source/drain region involves forming a drain region, and forming the second source/drain region involves forming a source region.

In one embodiment, forming the first source/drain region involves forming a source region, and forming the second source/drain region involves forming a drain region.

What is claimed is:

**1.** A semiconductor device, comprising:

a substrate with an uppermost surface having a first lattice constant;

a first source/drain region disposed on the uppermost surface of the substrate and having a second, different, lattice constant;

a vertical channel region disposed on the first source/drain region;

a second source/drain region disposed on the vertical channel region, wherein the second source/drain region has an upper lateral portion and a lower vertical portion, the lower vertical portion on the vertical channel region, and the lower vertical portion having first and second sides, wherein the upper lateral portion extends beyond both the first and second sides of the lower vertical portion, and wherein the upper lateral portion has a lateral width greater than a lateral width of the vertical channel region; and

a gate stack disposed on and completely surrounding a portion of the vertical channel region, wherein the gate stack is not in physical contact with the upper lateral portion of the second source/drain region.

**2.** The semiconductor device of claim **1**, further comprising:

a plurality of lattice defects confined to the first source/drain region, wherein the vertical channel region is essentially defect-free.

**3.** The semiconductor device of claim **1**, wherein the first and second source/drain regions comprise a semiconductor material different from a semiconductor material of the vertical channel region.

**4.** The semiconductor device of claim **3**, wherein the semiconductor material of the first and second source/drain regions is lattice mismatched from the semiconductor material of the vertical channel region, and wherein the first and second source/drain regions impart a strain to the vertical channel region.

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**5.** The semiconductor device of claim **1**, further comprising:

a first contact disposed on the uppermost surface of the substrate and electrically coupled to the first source/drain region through the substrate;

a second contact disposed on the second source/drain region; and

a gate contact disposed on a horizontal extension of the gate stack.

**6.** The semiconductor device of claim **1**, wherein the first source/drain region is a drain region, and wherein the second source/drain region is a source region.

**7.** The semiconductor device of claim **1**, wherein the first source/drain region is a source region, and wherein the second source/drain region is a drain region.

**8.** The semiconductor device of claim **1**, wherein the gate stack comprises a high-k gate dielectric layer and a metal gate electrode.

**9.** The semiconductor device of claim **1**, wherein a conductivity type of the first source/drain region is the same as a conductivity type of the second source/drain region, and wherein the semiconductor device is a MOS-FET device.

**10.** The semiconductor device of claim **1**, wherein a conductivity type of the first source/drain region is opposite to a conductivity type of the second source/drain region, and wherein the semiconductor device is a tunnel FET device.

**11.** A semiconductor device, comprising:

a substrate having a surface;

a first source/drain region disposed on the surface of the substrate;

a vertical channel region disposed on the first source/drain region;

a plurality of lattice defects confined to the first source/drain region, wherein the vertical channel region is essentially defect-free;

a second source/drain region disposed on the vertical channel region, wherein the second source/drain region has an upper lateral portion and a lower vertical portion, the lower vertical portion on the vertical channel region, and the lower vertical portion having first and second sides, wherein the upper lateral portion extends beyond both the first and second sides of the lower vertical portion, and wherein the upper lateral portion has a lateral width greater than a lateral width of the vertical channel region; and

a gate stack disposed on and completely surrounding a portion of the vertical channel region, wherein the gate stack is not in physical contact with the upper lateral portion of the second source/drain region.

**12.** The semiconductor device of claim **11**, wherein the first and second source/drain regions comprise a semiconductor material different from a semiconductor material of the vertical channel region.

**13.** The semiconductor device of claim **12**, wherein the semiconductor material of the first and second source/drain regions is lattice mismatched from the semiconductor material of the vertical channel region, and wherein the first and second source/drain regions impart a strain to the vertical channel region.

**14.** The semiconductor device of claim **11**, further comprising:

a first contact disposed on the surface of the substrate and electrically coupled to the first source/drain region through the substrate;

a second contact disposed on the second source/drain region; and

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a gate contact disposed on a horizontal extension of the gate stack.

15 **15.** The semiconductor device of claim **11**, wherein the first source/drain region is a drain region, and wherein the second source/drain region is a source region.

**16.** The semiconductor device of claim **11**, wherein the first source/drain region is a source region, and wherein the second source/drain region is a drain region.

10 **17.** The semiconductor device of claim **11**, wherein the gate stack comprises a high-k gate dielectric layer and a metal gate electrode.

15 **18.** The semiconductor device of claim **11**, wherein a conductivity type of the first source/drain region is the same as a conductivity type of the second source/drain region, and wherein the semiconductor device is a MOS-FET device.

**19.** The semiconductor device of claim **11**, wherein a conductivity type of the first source/drain region is opposite to a conductivity type of the second source/drain region, and wherein the semiconductor device is a tunnel FET device.

20 **20.** A method of fabricating a semiconductor device, the method comprising:

forming an insulator layer on a surface of a substrate;  
patterning the insulator layer to form an opening in the insulator layer, the opening exposing a portion of the surface of the substrate;

forming a first source/drain region in the opening, on the surface of the substrate;

forming a vertical channel region in the opening, on the first source/drain region;

forming a second source/drain region in the opening, on the vertical channel region, wherein the second source/drain region has an upper lateral portion and a lower vertical portion, the lower vertical portion on the vertical channel region, and the lower vertical portion having first and second sides, wherein the upper lateral

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portion extends beyond both the first and second sides of the lower vertical portion, and wherein the upper lateral portion has a lateral width greater than a lateral width of the vertical channel region;

5 recessing the insulator layer to expose a portion of the vertical channel region; and

forming a gate stack on and completely surrounding an exposed portion of the vertical channel region, wherein the gate stack is not in physical contact with the upper lateral portion of the second source/drain region.

10 **21.** The method of claim **20**, wherein forming the first source/drain region comprises forming a plurality of lattice defects confined to the first source/drain region, wherein the vertical channel region is formed essentially defect-free.

15 **22.** The method of claim **20**, wherein forming the first source/drain region comprises forming the first source/drain region having a lattice constant different than a lattice constant of the surface of the substrate.

20 **23.** The method of claim **20**, wherein forming the second source/drain region in the opening comprises forming a first portion of the second source/drain region in the opening, and forming a second portion of the second source/drain region above the opening and on a portion of an uppermost surface of the insulator layer.

25 **24.** The method of claim **20**, wherein forming the first source/drain region comprises forming a drain region, and wherein forming the second source/drain region comprises forming a source region.

30 **25.** The method of claim **20**, wherein forming the first source/drain region comprises forming a source region, and wherein forming the second source/drain region comprises forming a drain region.

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